Research Article

Analysis of a Substrate Integrated Waveguide Hybrid Ring (Rat-Race) Coupler

Ramin Dehdasht-Heydari,¹ Keyvan Forooraghi,² and Mohammad Naser-Moghadasi¹

¹ Department of Electrical Engineering, Science and Research Branch, Faculty of Engineering, Islamic Azad University, Tehran 14778 93855, Iran

² Department of Electrical Engineering, Faculty of Engineering, Tarbiat Modares University (TMU), Tehran 14115 111, Iran

Correspondence should be addressed to Ramin Dehdasht-Heydari; dehdashtheydari@yahoo.com

Received 24 January 2014; Revised 4 April 2014; Accepted 4 April 2014; Published 28 April 2014

Academic Editor: Francisco Falcone

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This paper presents an efficient analysis of a substrate integrated waveguide (SIW) single-layer hybrid ring coupler (rat-race) for millimeter-wave and microwave applications. The scattered field from each circular cylinder is expanded by cylindrical eigenfunctions with unknown coefficients that have been solved by electric and magnetic tangential boundary on each metallic via. The coupler S-matrix is calculated by using mode matching that uses the cylindrical vector expansion analysis to minimize the computational time and provides more physical insight. To achieve higher bandwidth, the radiuses of the coupler under analysis have been optimized in Matlab code by invasive weed optimization (IWO) method, and the results have been verified by CST package. The return loss and the isolation are less than -15 dB, and -18 dB, respectively. The insertion loss is divided equally -3 ± 0.2 dB, with 0 ± 5 and 180 ± 10 degrees in output ports over the operating frequency bandwidth and the agreement of phase differences in output ports has been examined objectively by feature selective validation (FSV) technique.

1. Introduction

The concept of substrate integrated waveguides was proposed [1] to overcome the drawbacks of conventional rectangular waveguide and has drawn much attention, for it can offer a promising solution to compact, low-cost, efficient, and hybrid integration of different kinds of conventional microstrip structures [2] in the same substrate at microwave and millimeter wave frequencies. In developing SIW base devices, many passive components, such as transitions, filters, oscillators, antennas, circulators, and couplers, have been studied in microwave and millimeter-wave systems [3–10].

The analysis of substrate integrated waveguide (SIW) structures has been carried out in many methods. For instance, the method of moments accompanied with the Floquet mode expansions [11], the finite-difference frequency domain (FDFD) method [12], the boundary integral-resonant expansion (BI-RME) method [13] and the method of lines [14] have been applied to determine the propagation characteristics of the substrate integrated waveguides (SIWs).

Moreover, the design of a real device mostly depends on the finite element method and the method of moment, which can be time consuming and memory demanding for large structures.

Recently, several papers have made use of a cylindrical vector wave (CVW) expansion in order to study the simplified 2D case [15–17] and the full 3D case [18–24]. These mode expansions allow an efficient full-wave analysis of SIW structures with metallic and dielectric posts. Furthermore, there is a need for using efficient methods of mode matching and CVW to analyze some specific structures such as couplers. The design of the SIW rat race coupler basically has been presented in [25] with transition from microstrip to SIW rat-race arms. However, in [25], the output phases results (i.e. phase differences of 0 and 180 degrees) of the coupler were not mentioned at all. In addition, the dimensions of the coupler should be optimized to achieve the more relative bandwidth. Because the analysis of the coupler has not been examined, its optimization has not been carried out properly in this case.

FIGURE 1: (a) Top view of the proposed rat-race coupler under analysis. (b) One via of rat-race coupler and its related waves.

In this paper, the dyadic Green's function in a cylindrical medium can be represented in terms of cylindrical vector wave eigenfunctions. So, at first we find the vector wave function for each PEC via in the SIW rat-race coupler structure which is excited by coaxial cables and shown in Figure 1. Because of using four coaxial cables instead of microstrip line transitions and a closed form of arms ($\lambda/4$ distance from the coaxial cables), our structure in this paper is of low loss and profile.

When these vector wave expansions are known, the dyadic Green's function for our rat-race coupler can be expressed in terms of these vector wave functions. By imposing boundary conditions on each via and transferring the obtained equations to matrix, we find the unknown coefficient of CVW. In the end, we find admittance matrix from the coefficients and conveniently we can reach scattering parameters of the proposed rat-race coupler. The mode-matching method has been implemented in Matlab software to compare the results with CST package. Also, to achieve better characteristics of rat-race coupler, we use an optimization with IWO and the optimized results are compared. It can be observed that the relative bandwidth has been increased from 9% to 17% over 11.4–13.7 GHz. In addition, the agreement of the output phase results has been shown clearly with feature selective validation (FSV).

2. Analysis of Rat-Race Coupler with Cylindrical Vector Wave (CVW) Expansion Formulations

As the structure in Figure 1(a) is a homogeneous medium, the electric and magnetic fields fulfill the following equations:

$$\nabla \times \nabla \times \mathbf{E}(\mathbf{r}) - k^2 \mathbf{E}(\mathbf{r}) = 0, \quad (1a)$$

$$\nabla \times \nabla \times \mathbf{H}(\mathbf{r}) - k^2 \mathbf{H}(\mathbf{r}) = 0, \quad (1b)$$

where k is the wave number in dielectric substrate and $k = \omega \sqrt{\mu_0 \epsilon_0 \epsilon_r}$.

Also, in a homogenous medium, $\mathbf{E}(\mathbf{r})$ and $\mathbf{H}(\mathbf{r})$ are derivable from scalar potential $\vartheta(r)$. Now, we can define two vector wave functions $\mathbf{P}(\mathbf{r})$ and $\mathbf{Q}(\mathbf{r})$ as the equivalence of an electric or a magnetic field. Notice that the above equation is valid for $\mathbf{Q}(\mathbf{r})$:

$$\nabla \cdot \mathbf{P}(\mathbf{r}) = 0, \quad \nabla \times \mathbf{P}(\mathbf{r}) \neq 0. \quad (2)$$

For consideration of the relation between $\vartheta(r)$ and $\mathbf{P}(\mathbf{r})$ and $\mathbf{Q}(\mathbf{r})$, let us assume the following equation for scalar potential:

$$(\nabla^2 + k^2) \vartheta(r) = 0, \quad (3)$$

and the relation between $\vartheta(r)$, $\mathbf{P}(\mathbf{r})$, and $\mathbf{Q}(\mathbf{r})$ is as follows:

$$\mathbf{P}(\mathbf{r}) = \nabla \times (\vartheta(r) \mathbf{a}_n), \quad (4)$$

$$\mathbf{Q}(\mathbf{r}) = \frac{1}{k} \nabla \times \mathbf{P}(\mathbf{r}), \quad (5)$$

where $\mathbf{a}_n$ is unit normal vector on the surface.

In a cylindrical coordinate we can express in each via in region 1 (outgoing region) this harmonic scalar potential $\vartheta_n(r)$:

$$\vartheta_n(r) = H_n^{(2)}(k_m \rho) e^{j(k_z z - n\varphi)}, \quad (6)$$

and $H_n^{(2)}$ indicates the Hankel function of the second kind, $k_m = \sqrt{k^2 - k_z^2}$, $k_z = m\pi/h$, and h is the height of substrate in Figure 1(a). In (6), m and n are the modes in vertical direction (z -direction) and azimuthal direction (φ -direction), respectively. Also, in this paper we consider the dependence of the SIW structure on the variation to z , which is expressed as an exponential term.

By using (6) in (4) and (5) we obtain $\mathbf{P}(\mathbf{r})$ and $\mathbf{Q}(\mathbf{r})$ for Figure 1(b):

$$\mathbf{P}_n(\mathbf{r}) = \left(\frac{-1}{\rho} j n e^{j(k_z z - n\varphi)} H_n^{(2)}(k_m \rho) \right) \mathbf{a}_\rho + (-k_m \rho H_n'^{(2)}(k_m \rho) e^{j(k_z z - n\varphi)}) \mathbf{a}_\varphi \quad (7a)$$

$$\mathbf{Q}_n(\mathbf{r}) = (j k_m k_z \rho H_n'^{(2)}(k_m \rho) e^{j(k_z z - n\varphi)}) \mathbf{a}_\rho + \left(\frac{1}{\rho} n k_z e^{j(k_z z - n\varphi)} H_n^{(2)}(k_m \rho) \right) \mathbf{a}_\varphi + (k_m e^{j(k_z z - n\varphi)} (-2 H_n'^{(2)}(k_m \rho) - \rho k_m H_n''^{(2)}(k_m \rho))) \mathbf{a}_z, \quad (7b)$$

where

$$H_n'^{(2)}(k_m \rho) = \frac{\partial}{\partial \rho} (H_n^{(2)}(k_m \rho)), \quad (8)$$

$$H_n''^{(2)}(k_m \rho) = \frac{\partial}{\partial \rho} (H_n'^{(2)}(k_m \rho)).$$

So, arbitrary electric and magnetic fields $E(r)$ and $H(r)$ in region 1 can be expressed as

$$H_{\text{total}}(r) = H_1 + H_2, \quad (9a)$$

$$E_{\text{total}}(r) = E_1 + E_2, \quad (9b)$$

where E_2 and H_2 are scattering electrical and magnetic waves from the via and E_1 and H_1 are incident waves from a magnetic source (M'_s) in the region 1. To calculate H_1 , we need this equation:

$$H_1 = -j\omega\epsilon \iiint G_{m2} \cdot M'_s dV', \quad (10)$$

where G_{m2} is the magnetic Green function of second kind [26, 27] which for parallel plate waveguide by using residue theorem in cylindrical coordination explicit form is given by

$$G_{m2}(\mathbf{r}, \mathbf{r}') = -\frac{\hat{\rho}\hat{\rho}'}{k_0^2} \delta(\mathbf{r} - \mathbf{r}') - \frac{1}{j4\pi} \sum_{m=0}^{N_z} \sum_{n=0}^{N_\varphi} (2 - \delta_{m0}) \frac{1}{k_m^2 h} \times [P_n(k_m, k_z, \rho) P_n'(k_m, k_z, \rho') + Q_n(k_m, k_z, \rho) Q_n'(k_m, k_z, \rho')], \quad (11)$$

$$\delta_{m0} = \begin{cases} 0 & \text{if } m \neq 0 \\ 1 & \text{if } m = 0, \end{cases} \quad (12)$$

where P_n and Q_n for $\rho > \rho'$ are similar as outgoing wave in region 1 for (7a) and (7b). For $\rho < \rho'$, the equations are replaced with $(J_n(k_m \rho))$ instead of $(H_n(k_m \rho))$. Also, P'_n and Q'_n can be achieved by interchanging $\rho < \rho'$ with $\rho > \rho'$

FIGURE 2: S_{11} of the rat-race coupler versus IWO iteration number.

FIGURE 3: The S-parameters versus frequency from analysis and CST.

and vice versa. The m and n in (11) are eigenvalues modes in vertical and azimuthal directions, respectively.

After obtaining H_1 from (10) the electrical field E_1 is obtained from

$$E = \frac{1}{j\omega\epsilon} \nabla \times H. \quad (13)$$

From (1a), (1b), and (3), we can write TE and TM modes for scattering waves (H_2, E_2) in region 1 as CVW expansions:

$$H_2(r) = \sum_{l=1}^{P_{\text{via}}} \sum_{m=1}^{N_z} \sum_{n=1}^{N_\varphi} (C_{l,m,n}^{\text{TM}} P_n + D_{l,m,n}^{\text{TE}} Q_n). \quad (14)$$

FIGURE 4: Phase responses of the SIW rat-race coupler: (a) in-phase response and (b) out-of-phase response.

By using (13),

$$E_2(r) = \sum_{l=1}^{P_{\text{via}}} \sum_{m=1}^{N_z} \sum_{n=1}^{N_\phi} (C_{l,m,n}^{\text{TM}} Q_n + D_{l,m,n}^{\text{TE}} P_n). \quad (15)$$

To determine unknown coefficients ($C_{l,m,n}^{\text{TM}}, D_{l,m,n}^{\text{TE}}$), the boundary conditions for the surface of each metallic should be imposed:

$$\hat{n} \times (E_1 + E_2) = 0 \quad (16)$$

in surface of each PEC post with radius a_i .

After imposing boundary conditions that span over the metal posts of sidewalls, arms, inner circle, inner conductor of coaxial cables, and four matching impedance metallic holes which are demonstrated in Figure 1(a), we can obtain a matrix (for TE and TM modes separately) for implantation in Matlab code. By using (16) the unknown coefficient vector $F_{l,m,n}^{\text{TM/TE}} = [C_{l,m,n}^{\text{TM}}, D_{l,m,n}^{\text{TE}}]$ can be expressed as

$$\begin{bmatrix} F_{1,m,0}^{\text{TM/TE}} \\ \vdots \\ F_{l,m,n}^{\text{TM/TE}} \end{bmatrix} = [\mathbf{U}]^{-1} [\mathbf{S}], \quad (17)$$

where U is interaction matrix between the vias and S is excitation vector.

In (17), for propagation modes, we use the direct inverse command in Matlab to obtain unknown coefficients, and, for nonpropagation modes, we use iteration methods because of the singularity.

The admittance formulation of four coaxial cables in Figure 1(a) is

$$Y^{(p_i, p_j)} = -\frac{\int \mathbf{H}^{p_i} \cdot \mathbf{M}'_{p_j}(\rho) d\mathbf{S}'}{|V|^2}, \quad (18)$$

where $\mathbf{M}'(\rho)$ is surface current and has the same distribution as the E field in a coaxial cable:

$$\mathbf{E}'(\rho) = \frac{V_0}{2\rho L n(b/a)} \mathbf{a}_\rho, \quad (19)$$

and with Schelkunoff's equivalence principle:

$$\mathbf{M}'(\rho) = -2\hat{n} \times \mathbf{E}(\rho). \quad (20)$$

With excitation of the coupler with coaxial cables, the scattering parameters of the coupler conveniently can be obtained from (18).

3. Optimization of the Rat-Race Coupler with IWO Algorithm

Invasive weed optimization (IWO) algorithm has been first used by Mehrabian and Lucas [28] in dynamic and control systems theory. The main parameters involved in improving the bandwidth of a SIW hybrid ring coupler with IWO are $R1$, $R2$, and $R3$. IWO parameters which are used for optimization are shown in Table 1. In our optimization, we consider a goal function (goal: $\text{Max}(S_{11}) \leq -15$ dB), and when we get to our goal after passing the necessary iterations, the other output results of the coupler will be satisfied. S_{11} variations of the hybrid ring coupler in interest band versus number of iterations are shown in Figure 2. As shown in this figure, the optimized value of S_{11} is -15 dB after 175 iterations number which corresponds to the $R1 = 4.5$ mm, $R2 = 6.5$ mm, and $R3 = 15.5$ mm over the 11.4–13.7 GHz bandwidth.

FIGURE 5: Continued.

FIGURE 5: Agreement cases for in-phase responses with 1D FSV tool: (a) ADMi and FDMi, (b) ADMc and FDMc, (c) GDMi and GDMc, and (d) GRADE/SPREAD chart.

TABLE 1: IWO parameters values for Figure 1(a).

Symbol	Quantity	Value
No	Number of initial population	5
$it_{\max}$	Maximum number of iterations	1000
dim	Problem dimension	3
$P_{\max}$	Maximum number of plant population	5
$S_{\max}$	Maximum number of seeds	25
$S_{\min}$	Minimum number of seeds	0
n	Nonlinear modulation index	3
σ_{initial}	Initial value of standard deviation	2
σ_{final}	Final value of standard deviation	0.01
$R1_{\text{ini}}$	Initial search area	2 mm to 20 mm
$R2_{\text{ini}}$		4 mm to 30 mm
$R3_{\text{ini}}$		10 mm to 45 mm

4. Feature Selective Validation (FSV)

Feature selective validation (FSV) is a very useful technique to compare the agreement of two plots usually to decide that the two plots have excellent, very good, good, fair, poor, or very poor agreement [29]. By using FSV, the comparison between results is to be measured objectively, eliminating the element of subjectivity from the decision making process.

The FSV technique is based on the decomposition of the results to be compared into two component measures and then the recombination of the results to provide a global goodness of fit measure. The components used are three figures of merit of the comparison of two data sets [30–33]:

- (1) the amplitude difference measure (ADM) that compares the amplitudes and trends of the two data sets,
- (2) the feature difference measure (FDM) that compares the rapidly changing features (as a function of the independent variable),

- (3) the global difference measure (GDM) that is obtained with combination of the ADM and FDM.

Accordingly, the comparison of two data sets can be ranked. This ranking is useful for making a selection between multiple comparisons. So, two quality factors for each figure of merit (ADM, FDM, and GDM) are regarded (i.e., the GRADE and the SPREAD).

The GRADE provides a numerical indication of the quality of the comparison and the SPREAD gives a numerical indication of the level of confidence that can be placed on this evaluation. In GRADE, the smaller it is, the better the comparison of the results is, and, in SPREAD, the higher the reliability is, the smaller it is. Furthermore, GRADE and SPREAD can be computed for each figure of merit and reported on a GRADE/SPREAD chart.

When we use FSV tool [34], there are time domain and frequency domain analyses. A time domain analysis is performed on two sets of data that are generic amplitude values.

In the case of frequency domain, there are three options to analyze:

- (1) magnitude option that the input data are magnitude values,
- (2) phase option that the input data are phase values,
- (3) combined option in which the 1D FSV combined analysis performs two FSV analyses (i.e., magnitude and phase) and combines them in a single result.

5. Result and Discussion

The formulations in Section 2 and IWO algorithm have been implemented in Matlab code. The S-parameters from analysis, after optimization of the structure in Section 3, are shown in Figure 3. The S_{11} (return loss) and S_{14} (isolation) over 11.4–13.7 GHz are less than -15 dB and -18 dB in the order mentioned and insertion loss is divided equally -3 ± 0.2 dB in

(a)

(b)

(c)

FIGURE 6: Continued.

FIGURE 6: Agreement cases for out-of-phase responses with 1D FSV tool: (a) ADMi and FDMi, (b) ADMc and FDMc, (c) GDMi and GDMc, and (d) GRADE/SPREAD chart.

TABLE 2: Simulation time on a Core i5 with 4 GB RAM (azimuthally mode numbers (n) = 7; vertically mode numbers (m) = 2).

Structure type in Figure 1	Number of metallic vias	CST CPU time Time domain	Analysis in this paper 50 frequency points
Hybrid ring (rat-race) coupler	330	1200 s	110 s

ports 2 and 3. The analysis results show excellent agreement with the simulation. Figure 4 shows relative phases for the rat-race coupler. The phase difference in Figure 4(a) is $0 \pm 5^\circ$ and in Figure 4(b) is $180 \pm 10^\circ$ over the interest band. Also, there is good agreement between the two proposed methods. Obviously, the relative bandwidth after optimization from Figures 3 and 4 is approximately 17%.

As an application of the FSV technique which has been explained in Section 4, the agreement of the output phase results in Figure 4 has been performed with 1D FSV tool 2.0.4 [32] in frequency domain. According to [34], excellent, very good, good, fair, poor, and very poor agreements fall in the ranges of [0 0.1), [0.1 0.2), [0.2 0.4), [0.4 0.8), [0.8 1.6), and [1.6 infinity), respectively. From Figure 5, it is observed that the FSV tool results show good and fair agreements for in-phase responses in the most range of the bandwidth of interest. Also, based on Figure 6, very good and excellent agreements have been obtained for out-of-phase responses in almost all of the operating frequency range.

To prove the efficiency of our analysis, simulation time for the considered case and comparing it to CST software are reported in Table 2. From this table, the run time ratio of the analysis related to CST is 1:10.9.

6. Conclusion

In this paper, the dyadic Green's function and vector wave functions for cylindrical coordination have been used for a SIW rat-race coupler. Our output results with the mode matching method after optimization with IWO and comparing it with CST using FSV technique and CPU time

show accuracy and efficiency of our theory, respectively. Throughout 11.4–13.7 GHz, the structure has 17% relative bandwidth. By using the proposed analysis and optimizing the dimensions of the coupler, the bandwidth can shift in the interested band.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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